NASA TECHNICAL TRANSLATION NASA TT F-16194

THE REACTION OF THE RESISTIVE AND CAPACITIVE VESSELS OF THE HAND AT THE START OF MUSCULAR EXERCISE

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(NASA-TT-F-16194) THE REACTION OF THE RESISTIVE AND CAPACITIVE VESSELS OF THE HAND AT THE START OF MUSCULAR EXERCISE (Kanner (Leo) Associates) 19 p HC $3.25 CSCL 06P N75-17938
Unclas
G3/52 10251

Translation of "La réaction des vaisseaux résistifs et capacitifs de la main au début de l'exercice musculaire" Journal de Physiologie, Vol. 68, Mar. 1974, p. 51-64

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. FEBRUARY 1975

STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TT F-16194		

4. Title and Subtitle	5. Report Date
THE REACTION OF THE RESISTIVE AND CAPACITIVE VESSELS OF THE HAND AT THE START OF MUSCULAR EXERCISE	February 1975
	6. Performing Organization Code
7. Author(s) J.M. Verpillat, A. Ghaem, B. Levy, and J. P. Martineaud, Physiology Depts. U.E.R. Lariboisière-St. Louis, University of Paris VIII & Biomedical U.E.R., Sts. Peres, U. of Paris V	8. Performing Organization Report No.
	10. Work Unit No.
9. Performing Organization Name and Address	11. Contract or Grant No. NASw-2481
Leo Kanner Associates, Redwood City, Calif. 94063	13. Type of Report and Period Covered: Translation
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration, Washington D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

Translation of "La réaction des vaisseaux résistifs et capacitifs de la main au début de l'exercice musculaire" Journal de Physiologie, vol. 68, Mar. 1974, p. 51-64

16. Abstract Heart rate (Fc), arterial blood flow (Q) by hand plethysmography, and variations in venous volume (Δ V) were measured in man during muscular exercise of varying levels of exertion (W) from 30 to 180 W. During short-term exercise (5 to 8 minutes), blood flow and volume change in the same way: an initial decrease is followed by a progressive increase. Maximal Δ V and minimal Q are not significantly linked with either W or Fc. These results show that the resistive and capacitive vessels of the hand, considered as representatives of cutaneous circulation, may be used as a flow and volume reserve at the beginning of exercise. However, due to the "all or nothing" type of the observed response it is not possible to attribute a precise regulating function to the cutaneous vessels.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Peripheral cutaneous circulation. Hand plethysmography. Muscular exercise. Skin blood flow. Skin veins.	Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified		

NASA-HQ

THE REACTION OF THE RESISTIVE AND CAPACITIVE VESSELS OF THE HAND AT THE START OF MUSCULAR EXERCISE

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Introduction /52

It has been known for a long time that muscular exercise effects not only the vascular networks of the muscles involved, but also the resistive and capacitive vessels of certain regions not directly affected by the increase in energy needs. Christensen and Nielsen (1942) have already shown that changes occur in both the arterial and venous circulation of the skin. However, there is still little known about the quantitative significance of these changes, and thus the role they may play in the operation of the circulatory system.

The purpose of this research was to determine the importance of the skin circulation as a blood flow and/or volume reserve during muscular activity. The choice was therefore made to study variations in the arterial blood flow and the volume of a preferential region of the skin, that of the hand. The vascular resistances of the skin are known to vary generally in the same direction (Greenfield, 1963); the skin of the hand is extremely reactive and its vascular changes are easy to measure.

In order to evaluate changes in cutaneous hemodynamic magnitudes, during leg exercise we monitored variations in hand blood flow, which indicate changes in arteriolar vasomotor tonus, and variations in blood volume in the hand, which are representative of the tonus of the venous wall and free circulation (Martineaud, et al, 1966).

Technique

Three male subjects participated in the experiment. The subjects were in good health, had sedentary occupations, were used to moderate physical activity, but without special athletic training, and were aged 25 to 40 years.

1. Conditions of Measurement

The exercises, which were short-term, were performed on a Fleisch ergometric bicycle, the subject being in dorsal decubitus, in a comfortable position with the head slightly raised. The levels of exertion requested were 30, 50, 70, and 90 watts (180 in some tests), at a pedaling rate of 60 rpm. To eliminate parasitic movements as much as possible, the left arm, which was used for the measurement, was abducted to approximately 90°. The forearm was in extension and the hand in semi-pronation.

The method used to measure the blood flow and the changes in blood volume was water plethysmography. The regions studied consisted of the left hand and wrist, raised to approximately the level of the heart. The blood pressure cuff was placed midway /53 down the forearm. Once the subject was in position, the pedaling produced only a minimum of involuntary movements and had little disturbing effect on the readings (Fig. 1). However, it was impossible to determine the blood volume variations of the hand with sufficient accuracy during the exercises at the highest level of exertion (180 watts).

The temperature of the plethysmograph was always 33° C., the skin temperature of the hand at rest. The ambient temperature was fixed at 22° C.

During some tests, the respiratory gaseous exchange, the arterial

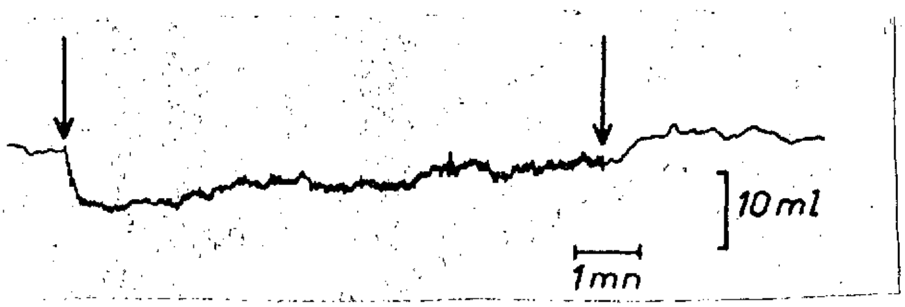

Fig. 1: Changes in the blood volume of the hand during leg exercise. The beginning and the end of the activity are marked by vertical arrows. One may note, first, spontaneous changes during rest, and second, artifacts due to the pedaling.

TABLE 1: HEART RATE (Fc) OXYGEN CONSUMPTION (Vo_2) AND DIASTOLIC ARTERIAL PRESSURE (P. A.) AT REST AND DURING MUSCULAR EXERCISES REQUIRING INCREASING EXERTION (AVERAGES FOR 3 SUBJECTS).

	Rest	30 watts	50 watts	70 watts	90 watts	180 watts
Fc/mn	72	97	109	119	125	175
$\dot{V}_{O_2}$ l_{STPD}/mn	0,230	0,700	0,910	1,140	1,370	1,845
P. A. mmHg	113-73	125-76	132-77	136-79	147-80	180-87

pressure and the heart rate were also measured (Table 1).

2. Test Procedures

All the experiments were performed during the afternoon, at least one hour after a consistently light meal. Immediately after arriving at the laboratory, the subject was placed in decubitus and his left hand placed in the plethysmograph, which was always filled with water at 33° C. After 20 minutes of rest, a series of blood flow measurements was performed or the blood volume of the hand was recorded for a few minutes. The exercise was then begun, with the subject having no knowledge of the level of exertion he would have to attain. Depending on the case, continuous measurements of the blood volume of the hand were made or the blood flow was determined once a minute. After 5 or 8 minutes the exercise was discontinued. Recovery, lasting 30 minutes, was monitored in the same way as above, while the heart rate returned to its initial level.

After this recovery period the same exercise was performed /54 once again. This time the blood flow or blood volume of the hand was measured, depending on the case. To decrease the error due to the scattering of individual values, at least 10 tests were performed with each subject at each level of exertion studied, for the volume as well as the flow. The 180 watt exercises were added after an ordinary test, since these required a long recovery period.

Results

The values of the blood flow and blood volume were always normalized to the volume of the limb segment actually introduced into the plethysmograph so as to be able to compare the measurements obtained from the various subjects, for whom the limb segment studied was not exactly the same.

1. Changes in the Blood Volume of the Hand

The variations in the volume of the hand were studied first as a function of time, and second, as a function of the level of exertion of the work performed.

a. Changes in Volume During Exercise

The variations in the average volumes of the various subjects as a function of time were comparable no matter what level of exertion was reached (Fig. 2 and Table 2). The venous volume began to decrease at the onset of activity, reaching its minimum value between the first and third minutes. The results were widely scattered, however, and the same subjects on different days might show a slight -- even zero -- decrease or a significant drop in hand volume at the same level of exertion.

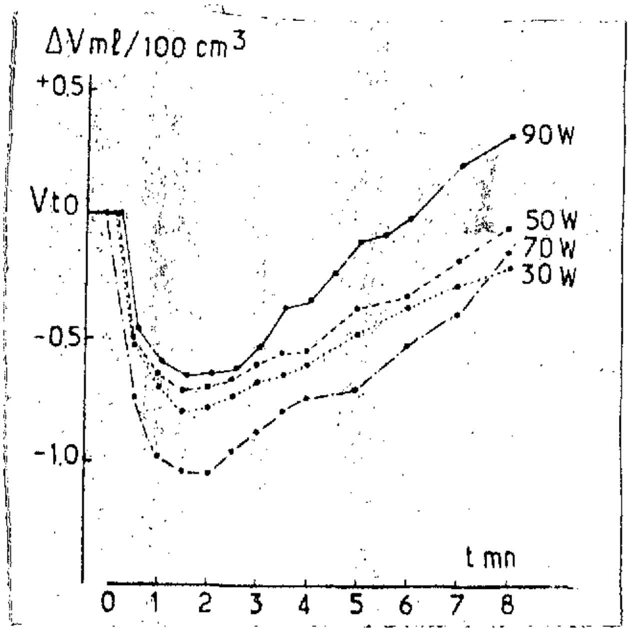

Fig. 2: Changes in the blood volume of the hand during exercises at different levels of exertion. Vt_o represents the volume of the hand at rest and ΔV the average of the volume variations of the three subjects.

In all cases, continuance of /55
the exercise was accompanied by a progressive increase in volume from the third minute on. It was not possible to determine a sharp difference in this increase according to the level of exertion; it could only be observed that at 8 minutes at a level of 90 watts, the volume had exceeded the starting value, while at the lowest level the volume was still lower than the values at rest.

b. Maximum Decrease in Hand Blood /56
Volume (Fig. 3)

The average of the maximum decreases in blood volume for all the tests at a given level of exertion was not proportional to this level. Instead, this maximum difference was comparable from one subject to the next, and the extreme individual values, independent of the level of exertion, were -0.52 ml/100cm^3

TABLE 2: CHANGES IN HAND VOLUME (IN ml/100 cm^3) DURING 8 MINUTES OF MUSCULAR EXERCISE AT INCREASING LEVELS OF EXERTION. (AVERAGES OF 3 SUBJECTS AND STANDARD DEVIATIONS).

	1 min	2 min	3 min	4 min	5 min	6 min	7 min	8 min
30 watts	−0,66 ±0,52	−0,74 ±0,56	−0,67 ±0,58	−0,59 ±0,69	−0,49 ±0,69	−0,35 ±0,66	−0,26 ±0,76	−0,20 ±0,77
50 watts	−0,57 ±0,44	−0,62 ±0,60	−0,55 ±0,66	−0,51 ±0,67	−0,36 ±0,65	−0,31 ±0,71	−0,16 ±0,69	−0,06 ±0,66
70 watts	−0,99 ±0,57	−1,09 ±0,63	−0,94 ±0,66	−0,84 ±0,69	−0,67 ±0,65	−0,49 ±0,72	−0,36 ±0,78	−0,21 ±0,76
90 watts	−0,57 ±0,51	−0,62 ±0,61	−0,51 ±0,62	−0,32 ±0,71	−0,10 ±0,85	−0,01 ±0,88	+0,22 ±0,91	+0,34 ±0,94

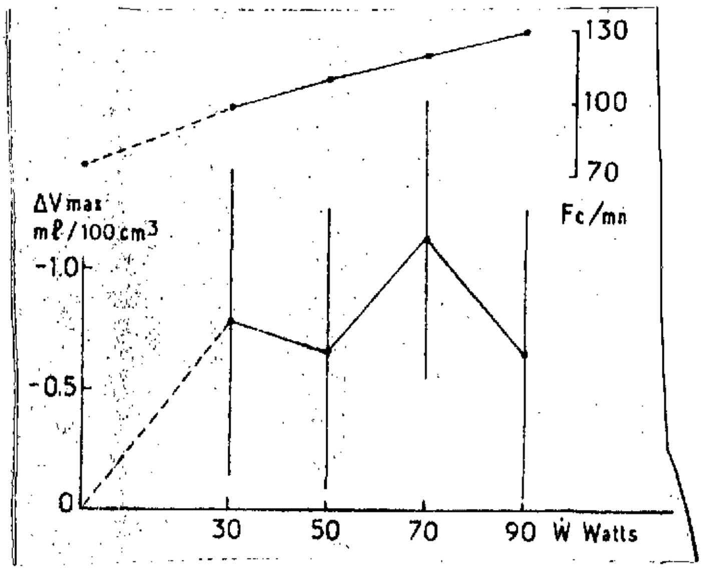

Fig. 3: Decrease in hand blood volume and in heart rate for exercises at different levels of exertion. ΔV max. is the maximum decrease in volume (average of the 3 subjects and standard deviation). Point 0 represents the volume of the hand at rest. Fc is the average heart rate mea-measured at rest and during the last minute of exercise.

(50 watts) and -1.32 ml/100 cm^3 (70 watts). There was an extremely broad scattering of individual values; at a given level of exertion in a single subject, the maximum drop in volume sometimes differed widely from one day to the next, without any apparent relationship between the change in volume and the manner in which the exercise was tolerated.

Finally, the maximum decrease in volume of the hand was examined as a function of heart rate measured immediately prior to stoppage.

of the exercise, but no relationship between these two magnitudes was found (correlation zero; r = 0.03; DDL = 12) (Fig. 4).

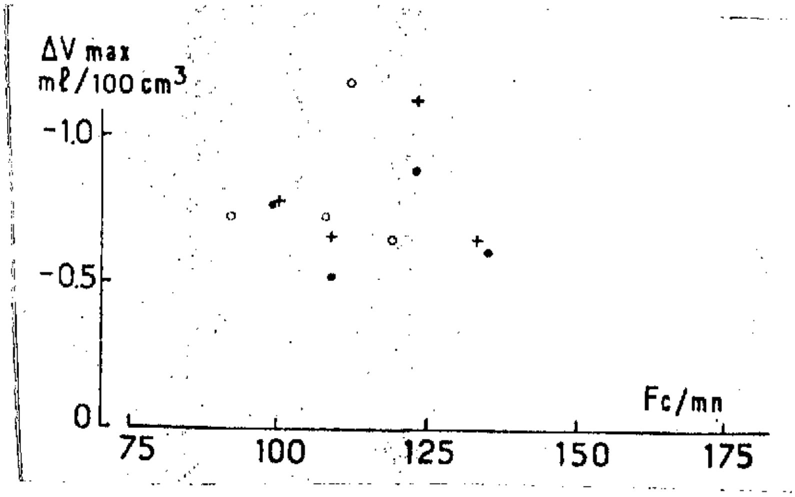

Fig. 4: Maximum decrease in hand blood volume as a function of heart rate. ΔV max. is the maximum decrease in volume (averages for each of the three subjects). Fc is the heart rate measured during last minute of exercises of different levels.

2. Blood Flow in the Hand

The blood flow was also studied as a function of time and as a function of the level of the exercise.

a. Changes in Blood Flow During Exercise

Although there was a considerable difference between initial values, the variations in hand blood flow were quite comparable from subject to the next (Fig. 5 and Table 3) and for a given subject from one experiment to the next. The flow underwent a sharp drop at the beginning of activity, with the minimum flow being observed at the 30th second in a large number of cases and always prior to the end of the second minute. The scattering of the results was of course quite significant, but the reproducibility of the initial drop was fairly high, contrary to our observations with the blood volume.

In all cases, the continuance of activity was accompanied by a more or less marked, but always precocious, increase in blood flow in the hand. This is why the exercises were discontinued after five minutes during the determination of blood flow. /57

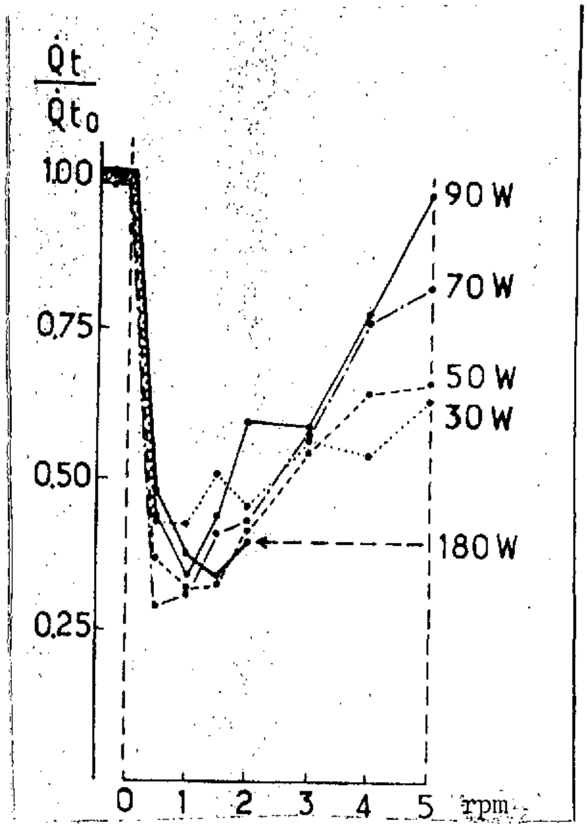

Fig. 5: Changes in the blood flow of the hand during exercises at different levels of exertion. $\dot{Q}t/\dot{Q}t_o$ is the ratio of the flow during exercise to the flow at rest (average of all three subjects). The 30 W, 50 W, 70 W, and 90 W exercises were continued for 5 minutes, and the 180 W exercises for only 2 minutes.

b. Minimum Blood Flow as a Function of the Level of Exertion

For the sum total of tests, the maximum drop in blood flow, independent of time, was always higher than half the initial value (Fig. 6 and Table 4). The extreme relative values of the minimum flow were 60% (30 watts) and 15% (180 W.) of the blood flow at rest.

The average drop in blood flow, considered as a relative or an absolute value, did not seem to be proportional to the level of exertion of the exercise. On the contrary, some findings gave the impression that the flow tends toward a stable minimum value for a given subject, independent of the blood flow prior to activity.

Finally, the minimum blood flow was compared with the heart rate measured during the last minute of activity; no evidence of a relationship between these two factors was found (correlation zero; r = 0.04; DDL = 12) (Fig. 7). /58

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TABLE 3: BLOOD FLOW IN THE HAND (IN ml/min; 100 cm) DURING MUSCULAR EXERCISE AT INCREASING LEVELS EXERTION IN COMPARISON WITH BLOOD FLOW AT REST. (AVERAGES OF THE THREE SUBJECTS AND STANDARD DEVIATIONS)

	Rest	30 sec	1 min	1 min 30 s	2 min	3 min	4 min	5 min
30 watts	10,69 ±5,15	4,69 ±3,33	4,78 ±4,17	5,46 ±4,59	4,86 ±4,23	6,26 ±5,88	5,77 ±4,15	6,76 ±4,98
50 watts	9,68 ±5,38	3,58 ±2,68	3,06 ±1,21	3,19 ±2,10	4,04 ±3,94	5,26 ±5,13	6,23 ±3,35	6,37 ±3,93
70 watts	8,01 ±5,85	2,33 ±1,39	2,48 ±2,08	3,31 ±3,06	3,45 ±3,00	4,66 ±3,33	6,10 ±6,25	6,59 ±4,69
90 watts	7,85 ±4,79	3,45 ±2,69	2,68 ±1,58	3,47 ±3,06	4,70 ±4,57	4,61 ±3,89	6,07 ±4,93	7,65 ±5,25
180 watts	11,06 ±5,83	5,34 ±4,45	4,16 ±2,30	3,77 ±2,60	4,47 ±3,28	—	—	—

TABLE 4: BLOOD FLOW IN THE HAND DURING MUSCULAR EXERCISE AT INCREASING LEVELS OF EXERTION AS A PERCENTAGE OF THE VALUE AT REST (AVERAGES OF ALL 3 SUBJECTS).

	30 sec	1 min	1 min 30 s	2 min	3 min	4 min	5 min
30 watts	43,8	42,8	51,1	45,4	58,5	53,9	63,2
50 watts	36,9	31,6	32,9	41,7	54,3	64,3	65,8
70 watts	29,1	30,9	41,1	43,1	58,2	76,1	82,3
90 watts	43,9	34,1	44,2	59,9	58,7	77,3	97,4
180 watts	48,3	37,6	34,1	40,4	—	—	—

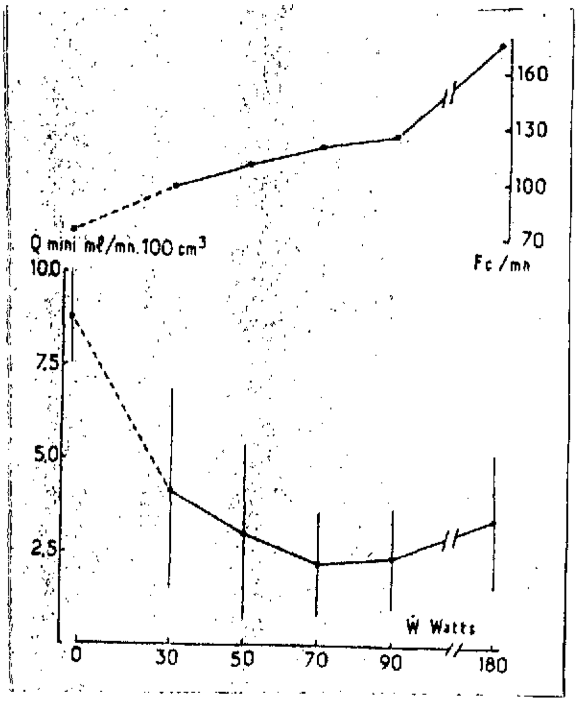

Fig. 6: Minimum blood flows in the hand and heart rate during exercises at different levels. Q mini is the absolute minimum blood flow (average of 3 subjects and standard deviation). For W = 0 the value of the blood flow is measured at rest. Fc is the average heart rate measured at rest and during the last minute of exercise.

Discussion

Findings made with regard to /60 blood circulation in the hand are generally applied to the entire skin circulation. First of all, the blood flow in the hand and changes in the venous volume of the hand may be considered representative of the cutaneous blood flow and volume; at this level the blood volume of the skin is high in comparison to the volume of the other constituents, whose circulatory characteristics are generally low in comparison to those of the skin; in addition, the method of measurement used basically involves the skin (Greenfield, 1963). Second, changes related to the start of the exercise are primarily determined by means of the cutaneous vessels (Muth et al, 1958; Blair et al, 1961; Greenfield, 1963; Bevegard and Shepherd 1966; Zelis and Mason, 1969).

Variations in vasomotor tonus, on the other hand, are of greater amplitude in the hand than in most other regions of the skin. Since the extremities of the arms and legs and the face are commonly exposed to heat stimuli of wide amplitude, they are more reactive. However, assuming the validity of the skin temperature variations at least, the blood flow in the different regions varies in the same direction (Greenfield, 1963), with one exception: the skin of the forehead, whose base blood flow is high and undergoes virtually no change under normal circumstances. As for variations in the venous volumes of various skin regions, very little is known in this area; the superficial veins of the arms, legs, hands and feet are merely known to have the same reactions to exercise (Bevegard and Shepherd, 1965; Samueloff et al, 1966)

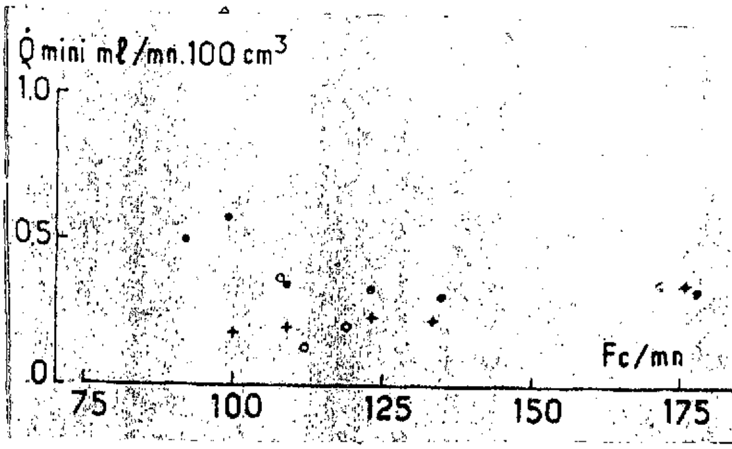

Fig. 7: Maximum decrease in blood flow in the hand as a function of heart rate. Q mini is the absolute minimum blood flow during exercises at different levels of exertion (averages of each of the 3 subjects). Fc is the heart rate measured during the last minute of exercise.

1. Behavior of the Resistive Vessels During Exercise

Christensen and Nielsen (1942) found the drop in cutaneous blood flow in the hand to be greatest during intense exercise, and this has subsequently been confirmed (Bevegard and Shepherd, 1965, a, 1966, 1967). This finding leads to the question of whether there is a proportional relationship between the strenuousness of the exercise and the decrease in cutaneous blood flow. If this were the case, the resistive cutaneous vessels could play an extremely important role in the reactivity of the region to high pressure during the initial phase of muscular exercise, and especially in the maintenance of arterial pressure. Now, the absence of any relationship between heart rate and blood flow in the hand shows that, under the conditions chosen, the control of vasomotricity works on an all or nothing basis.

This may be explained by the circumstances under which reserve blood is brought into play. The cutaneous arteriolar resistances are the object of twoo opposing excitations: a vasoconstrictive stimulus linked to the use of a reserve blood flow to supply the active regions, and a vasodilative stimulus linked to the necessities of temperature regulation. The amplitude of the drop is a result of these two types of stimuli. Thus, even though there is a relationship between the increase in vasoconstrictive tonus of sympathetic origin and the intensity of the exercise, it is not very logical that the level of exertion and the blood flow could be proportional under ordinary circumstances (Ghaem et al, 1973).

Nevertheless, in all experiments the beginning of activity is always accompanied by drop in blood flow; thus in all cases the cutaneous circulation places a reserve blood flow at the disposal of /61
the peripheral circulation. The minimum cutaneous blood flow is reached very quickly; during the same time, the blood flow in the active muscles reaches its maximum value (Clausen and Lassen, 1971), before the cardiac blood flow reaches its stable level (Jones, et al, 1970).

Thus the ecomony of cutaneous blood flow permits adequate perfusion of the active tissues. As a result, under neutral temperature conditions and during exercise performed in decubitus, the cutaneous blood flow reserve plays an important part in initial cardialvascular reaction. Subsequently it must be relieved by the blood flow from other regions active throughout the period of activity, especially the hepatosplanchnic blood flow reserve (Rowell, et al, 1964; Clausen and Trap-Jensen, 1971).

Attempts have been made to apply the findings obtained on the hand to the entire integument (Seroussi et al, 1969). There are two objections to this. First, the blood flow in the hand, which is extremely high at rest, reacts strongly to exercise, with the result that it is impossible to generalize the values of the differences in blood flow measured in the hand. If the skin of the hand is representative of the rest of the integument, however, extrapolation of the relative decrease is legitimate. Second, the blood flows in the regions of the skin close to the active muscles undergo somewhat different variations (Trap-Jensen et al, 1971). At low levels of exertion these flows increase at the outset, at average levels of exertion they undergo an initial drop followed by a resumption of their upward trend, and at high levels of exertion they may reach an almost zero level. During relatively intense exercise there are a great many regions of the skin close to active muscles.

Figures can be given only with some caution. For exercises whose levels of exertion correspond to 0.5 V_{O2} max, the 50% drop observed in the hand would correspond to the involvement of a reserve blood flow of approximately 250 ml/mn, for all skin in which the blood flow at rest is 400-500 ml/min.

2. Behavior of Capacitive Vessels During Exercise

Contrary to the initial findings of Christensen and Nielsen (1942), Bevegard and Shepherd (1966) have shown that there could be a relationship between the intensity of muscular exercise and the change in tonus of the superficial veins. This reaction also involves the veins close to the active muscles (Bevegard and Shepherd, 1965b). However, in free circulation no proportional relationship has been found between the involvement of the heart, evaluated on the basis of the heart rate, and that of the capacitive vessels. Similarly, control of the cutaneous veins seems to work on an all or nothing basis. It maybe noted that experiments which have demonstrated another method ofinvolvement have been performed on sections of blood vessels isolated from the rest of the circulatory system by a tourniquet (Bevegard and Shepherd, 1965a; Samueloff et al, 1966), under highly artificial conditions. The tonus of the venous smooth muscle is only one component of the venous volume; the local blood flow, regulated by the arteriolar vasomotricity, is another, and the times required to bring them into play are not the same. This might explain some of the experimental differences.

However, under the usual conditions (subject not having eaten, and in the comfort temperature zone), at the beginning of exercise /62 there is a redistribution of blood volume which generally involves the cutaneous regions. The latter make a reserve blood supply temporarily available to the blood flow in the heart, contributing to the increase in heart rate. The time the hand takes to reach its minimum value is roughly the same as that required by the heart flow to reach its stable level (Jones et al, 1970; Clausen at Trap-Jensen, 1971). The cutaneous blood volume may thus effectively participate in maintaining the central venous pressure until a fraction of the post-systolic ventricular residue has been used up. The cutaneous blood volume is brought into play at approximately the same time as the splanchnic blood volume (Wade and Bishop, 1962; Rowell et al, 1964).

Under unusual circumstances, however, the cutaneous circulation is unable to come into play. During exposure to intense cold the superficial blood volume decreases heavily, with the result that the increase in venous tonus in the skin which does still occur becomes quantitatively ineffective (Martineaud et al, 1970; Ghaem et al, 1971). On the other hand, when the skin temperature is too high (38° C. or above) there is no longer any modification of the venous tonus (Bevegard ant Shepherd 1966; Martineaud et al, 1970; Zitnik et al, 1971), while the cutaneous blood volume is greater than under the basal conditions. Even in the neutral temperature zone, the veins of the skin sometimes do not serve the function of restoring a reserve volume; it was seen earlier that, even in the laboratory, the drop in blood volume of the hand was not constant. This does not mean that muscular activity becomes any less normal. It is therefore clear that this cutaneous blood contribution is not indispensable to circulatory equilibrium (Robinson and Wilson, 1968).

One may attempt to estimate the quantity of blood used to contribute to the heart reaction. The deep-lying veins of the limbs are known to have no sympathetic innervation (Zelis and Mason, 1969); thus the change in blood volume in the hand represents the involvement of the venous blood of the skin. Since one-third of the tissue of the hand is skin (Greenfield, 1963), 1 ml of blood per 100 cm of hand tissue would actually correspond to 3 ml of blood per 100 cm of skin; for an overall quantity of skin weighing approximately 3.5 kg, the cutaneous blood volume brought into play during this type of exercise could be 100 ml. However, it remains to be shown that the skin of the rest of the body behaves in the same manner as that of the hand.

Conclusions

Superficial veins and arteries react to the start of muscular exercise by an increase in tonus while the various cardiovascular magnitudes are still adjusting to the increased metabolism. The response of the capacitive vessels, which is not absolutely constant like that of the resistive vessels, appears to occur on an all or nothing basis. The absence of any relationship between the tonus of the cutaneous veins and arterioles and the levels of exertion during the exercise bring the precise regulatory function of these changes into question. The actual specificity of the cutaneous vascular response has been discussed by some investigators (Arvidsson et al, 1970).

However, in the comfort temperature zone, the blood flow re- /63
serves made available in the high-pressure region and the volume reserves brought into play in the low-pressure region represent an appreciable contribution to the immediate regulation of the heart rate. The blood flow saved at the expense of cutaneous perfusion makes it possible to increase the flow of the active region without a proportional increase in overall blood flow; the volume of blood brought into play contributes to an increase in venous return and

in heart rate.

When the exercise is continued beyond the initial phase, the circulatory function of the cutaneous vessels is supplanted by their role in the mechanism of temperature regulation. Due to these secondary modifications, it is impossible for the superficial circulation to participate in the precise regulation of the cardiovascular magnitudes during exercise. However, these secondary modifications do not prevent the superficial circulation from playing an important part at the start of exercise.

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